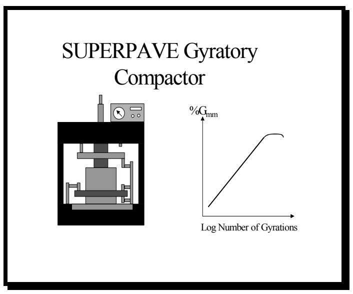
STANDARD PRACTICE FOR SUPERPAVE VOLUMETRIC MIX DESIGN FOP FOR AASHTO R 35

Significance

This FOP for Superpave volumetric mix design evaluation uses aggregate and mixture properties to produce a hot-mix asphalt (HMA) job-mix formula based on the volumetric properties in terms of air voids (V_a), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA).



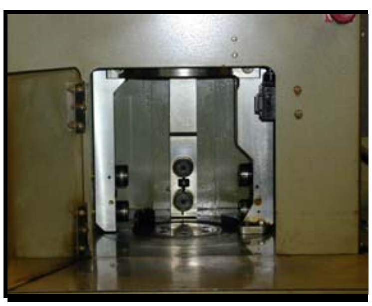
02 Scope

Superpave design and analysis includes:

- Volumetric mix design
- Performance based tests
- Performance prediction

This FOP provides the basic steps needed to produce an HMA mixture that meets the Superpave HMA volumetric mix design requirements.

The Superpave gyratory compactor is the method of compaction for laboratory and field control testing and evaluation of the HMA mixtures.



03 Mix Design Overview

The major steps that must be conducted for the successful completion of the Superpave mix design process are:

- Evaluating trial gradations
- Selection of optimum binder content

04 Prerequisite Tests

- AASHTO T 2 Sampling of Aggregates
- AASHTO T 248 Reducing Samples of Aggregate to Testing
- AASHTO T 11 Materials Finer than 75µm (No. 200) Sieve in Mineral Aggregate by Washing
- AASHTO T 27 Sieve Analysis of Fine and Coarse Aggregates
- AASHTO T 85 and T 84 Specific Gravity of Coarse and Fine Aggregates

05 Definition of Terms

- G_{mm} = theoretical maximum specific gravity
- G_{mb} = measured bulk specific gravity
- G_{sb}(OD) = bulk specific gravity (oven-dry) of aggregate
- G_{sa} = apparent specific gravity of aggregate
- G_{se} = effective specific gravity of aggregate
- G_b = specific gravity of the binder
- 06 V_a = air voids
- VMA = voids in mineral aggregate
- VFA = voids filled with asphalt (binder)
- V_{ba} = absorbed binder volume
- V_{be} = effective binder volume
- P_b = percent binder content
- P_{ba} = percent absorbed binder
- P_{be} = percent effective binder content
- 07 P_s = percent of aggregate
- $P_{.075}/P_{be}$ = dust to effective binder ratio
- RAP = Reclaimed Asphalt Pavement
- Nominal Maximum Aggregate Size:
  One sieve size larger than the first sieve to cumulatively retain more than 10%
- Maximum Aggregate Size:
  One sieve size larger than the nominal maximum aggregate size
- 08 Design ESALs:
  Design equivalent 18,000 lbs (80kN) single axle load

  Note: Design ESALs are the anticipated project traffic level expected over a 20-year period. For pavements designed for more or less than 20 years standard load equivalent factors are used. ESALs should be calculated for a 20-year design life.

09 Selecting Design Aggregate Structure

1. Establish trial blends
2. Establish initial trial binder content
3. Compact specimens
4. Evaluate trial blends
5. Select design aggregate structure

10 Establish Trial Blends

Specifications for aggregate gradation are usually given as upper and lower limits on certain sieve sizes. Within these upper and lower limits, numerous aggregate gradations can be fabricated.

- Any Combined Gradation which meets AASHTO M 323 gradation controls is acceptable as a trial blend (see table 3 of FOP for AASHTO M 323)
- Select a minimum of 3 blends for design work
- Check all three blends against aggregate specifications

11 Preparing Aggregate Blend Gradations

1. Select binder in accordance with AASHTO M 320
   - Obtain specific gravity of binder (G_b) (AASHTO 228)
2. Obtain samples of aggregate from proposed stockpiles (AASHTO T 2) and reduce (AASHTO T 248.)
3. Wash and grade the samples (AASHTO T 11/T 27).
4. Determine bulk (G_{sb}) and apparent (G_{sa}) specific gravities for each coarse and fine aggregate portion (AASHTO T 85 and T 84)
5. Obtain the specific gravity of mineral filler (AASHTO T 100).

Using the following equation combine the aggregate fractions and absorptions:

$$P = Aa + Bb + Cc + \ldots\ldots Nn.$$

Where:

P = percent passing for combined aggregates

A, B, C…N = Percent passing for aggregates A, B, C, etc. expressed as whole percentages.

a, b, c …n = Percentage of aggregates A, B, C used, expressed as a decimal, totaling 1.00.

The three trial aggregate blend gradations are plotted on a 0.45-power gradation analysis chart. Confirm that each trial blend meets Tables 3 and 4 of the FOP for AASHTO M 323

Figure 1 is an example of a gradation plot of three acceptable trial blends.

Figure 1

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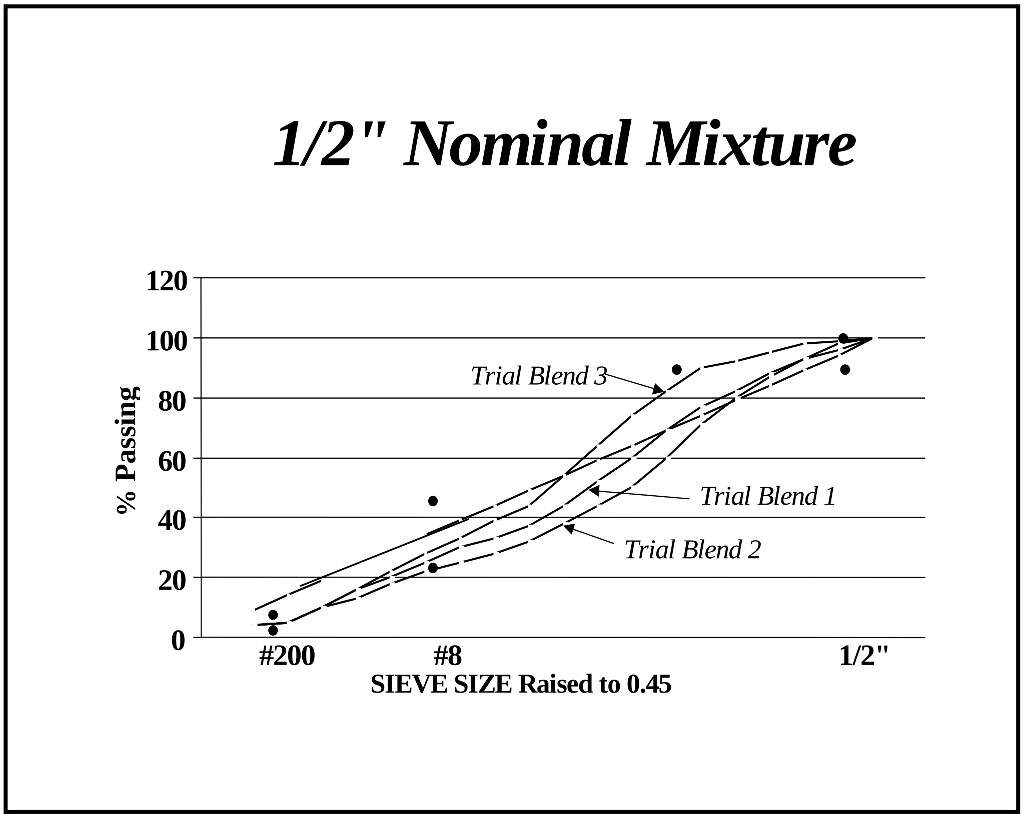

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Check Blends for Compliance

Conduct quality tests on each trial blend to confirm they meet minimum quality requirements specified in Table 5 of the FOP for AASHTO M 323

- Coarse Aggregate Angularity (AASHTO TP 61)
- Fine Aggregate Angularity (AASHTO T 304)
- Sand Equivalent (AASHTO T 176)
- Flat and elongated particles (ASTM D4791)

NOTE: The designer may elect to perform quality tests on each stockpile and estimate the combined results.

Table 1 – Aggregate Blending Worksheet

Product Identification	Percentage of Products Used (Decimal)				
	Blend No. 1	**a** (1/2")	**b** (3/8")	**c** (1/4")	**d** (Fine)
A (1/2")	**0.20**	0.20			
B (3/8")	**0.28**		0.28		
C (1/4")	**0.12**			0.12	
D (Fine)	**0.40**				0.40
Total	**1.00**	0.20	0.28	0.12	0.40

Grading for 1/2" (12.5 mm mix)						Individual Product Identification and Gradations (Cumulative Percent Passing)				
Sieve Size	**Comb.**	Individual Product Contributions				Sieve Size	**A** (1/2")	**B** (3/8")	**C** (1/4")	**D** (Fine)
1"	**100**	20.0	28.0	12.0	40.0	1"	100	100	100	100
3/4"	**100**	20.0	28.0	12.0	40.0	3/4"	100	100	100	100
1/2"	**98**	18.2	28.0	12.0	40.0	1/2"	91	100	100	100
3/8"	**81**	2.4	26.9	12.0	40.0	3/8"	12	96	100	100
No. 4	**55**	0.4	5.6	9.0	40.0	No. 4	2	20	75	100
No. 8	**45**	0.4	4.2	2.5	38.0	No. 8	2	15	21	95
No. 16	**34**	0.4	1.4	1.2	31.2	No. 16	2	5	10	78
No. 30	**20**	0.2	0.6	0.6	18.4	No. 30	1	2	5	46
No. 50	**11**	0.2	0.6	0.4	10.0	No. 50	1	2	3	25
No. 100	**8**	0.2	0.6	0.4	7.2	No. 100	1	2	3	18
No. 200	**4.8**	0.1	0.4	0.2	4.1	No. 200	0.3	1.5	2.0	10.3
Combined Specific Gravity and Absorption Data						Individual Aggregate Specific Gravity and Absorption Data				
G_{sb} (OD)	**2.623**	0.525	0.734	0.315	1.049	G_{sb} (OD)	2.643	2.641	2.589	2.610
G_{sb} (SSD)	**2.643**	0.529	0.740	0.317	1.057	G_{sb} (SSD)	2.655	2.654	2.626	2.635
G_{sa}	**2.677**	0.535	0.750	0.321	1.071	G_{sa}	2.673	2.676	2.689	2.677
Absorption	**0.684**	0.080	0.126	0.118	0.360	Absorption	0.40	0.45	0.98	0.90

Additional Design Information for Calculation of P_{bi}	
Binder Specific Gravity G_b	1.022
Log S_n (12.5)	1.0969

14 Establish Initial Trial Binder Content

The initial trial binder content is established to provide a good starting point for the mix design process. The binder content is estimated based on the theoretical relationship between aggregate properties and volumetric properties of the mix.

Estimate the binder content that will result in the trial compacted specimens having air voids close to 4% at N_{des} by using the following steps:

1. Obtain the binder specific gravity (G_b)
2. Calculate bulk specific gravity of the aggregate blend, G_{sb}(OD), and apparent specific gravity of the aggregate blend, G_{sa}
3. Estimate effective specific gravity of aggregate, G_{se_est}, using:
    - Bulk specific gravity of the aggregate blend, G_{sb}(OD)
    - Apparent specific gravity of the aggregate blend, G_{sa}
4. Calculate volume of absorbed binder, V_{ba}
5. Calculate volume of effective binder, V_{be}
6. Calculate trial binder content, P_{bi}

15 Specific Gravity of Blend

The bulk specific gravity and apparent specific gravity of each blend are determined using the law of partial fractions in two different ways:

a) Measure the specific gravity of the individual stockpiles and use the stockpiles percentages to determine the blend's specific gravity or

b) Measure the specific gravity directly on the trial blends.

Approach b) is more direct than a) because the measured specific gravity represents the exact blend, although the specific gravity would need to be determined again after any gradation changes.

Aggregate Specific Gravity Calculation

$$G_{sb}(OD) = \frac{P_1 + P_2 + P_3 + \ldots\ldots P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \frac{P_3}{G_3} + \ldots\ldots \frac{P_n}{G_n}}$$

$$G_{sa} = \frac{P_1 + P_2 + P_3 + \ldots\ldots P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \frac{P_3}{G_3} + \ldots\ldots \frac{P_n}{G_n}}$$

Where:

$P_1, P_2, P_3 \ldots\ldots P_n$ = Percentage of each aggregate used (totaling 100).

$G_1, G_2, G_3 \ldots\ldots G_n$ = Specific Gravity of each aggregate (bulk or apparent).

Calculation Examples using data from **Table 1 – Aggregate Blending Worksheet**

$$G_{sb}(OD) = \frac{100}{\frac{20}{2.643} + \frac{28}{2.641} + \frac{12}{2.589} + \frac{40}{2.610}} = 2.6226, \text{ say } 2.623$$

$$G_{sa} = \frac{100}{\frac{20}{2.673} + \frac{28}{2.676} + \frac{12}{2.689} + \frac{40}{2.677}} = 2.6774, \text{ say } 2.677$$

17 **Estimated Effective Specific Gravity of Aggregate**

The effective specific gravity of aggregate describes the ability of the aggregate blend to absorb the binder. It is calculated using an empirical relationship between the bulk specific gravity and the apparent specific gravity of the blend. A highly absorptive aggregate absorbs more binder, which in turn reduces its effective specific gravity because the binder is lighter than the aggregate particles.

$$G_{se\_est} = G_{sb} + \left(0.8\left(G_{sa} - G_{sb}\right)\right) \qquad 18$$

where:

G_{se_est} = Estimated effective specific gravity of the aggregate blend
G_{sb}(OD) = Bulk specific gravity (oven-dry) of the aggregate blend
G_{sa} = Apparent specific gravity of the aggregate blend

Note: The 0.8 factor can be changed at the designer's discretion. Absorptive aggregates may require a factor closer to 0.5 – 0.6.

Calculation Example (Specific Gravity data from previous calculation examples, page 3-7)

$$G_{se\_est} = 2.623 + \left(0.8\left(2.677 - 2.623\right)\right) = 2.6662, \text{ say } 2.666$$

Estimated Volume of Absorbed Binder

Estimate the volume of binder absorbed into the aggregate.
First calculate the value of W_s, then that of V_{ba}.

$$W_s = \frac{P_s(1 - V_a)}{\frac{P_b}{G_b} + \frac{P_s}{G_{se\_est}}} \qquad 19$$

$$V_{ba} = W_s\left(\frac{1}{G_{sb}} - \frac{1}{G_{se\_est}}\right)$$

where:

W_s = Mass of aggregate (grams) in 1 cm^3 of mix
V_{ba} = Estimated volume (cm^3) of absorbed binder in 1 cm^3 of mix
P_s = Mass percent of aggregate estimated, in decimal equivalent (assumed to be 0.95)
V_a = Volume of air voids (assumed to be 0.04 cm^3 in 1 cm^3 of mix)
P_b = Mass percent of binder estimated, in decimal equivalent (assumed to be 0.05)
G_b = Specific gravity of the binder
G_{se_est} = Estimated effective specific gravity of the aggregate blend
G_{sb} = Bulk specific gravity of the aggregate blend

Estimated Volume of Effective Binder

Only the unabsorbed binder is available to bind the aggregates. This is referred to as the "effective binder."

$$V_{be} = 0.176 - (0.0675 \times \mathrm{Log}(S_n)) \qquad 20$$

V_{be} = Volume of Effective Binder
S_n = Nominal Maximum Size of aggregate blend (mm)

NOTE: This regression equation is derived from an empirical relationship between: (1) VMA and V_{be} when the air void content, V_a, is equal to 4.0 percent: V_{be}=VMA-P_a=VMA-4.0; and (2) the relationship between VMA and the nominal maximum sieve size of the aggregate in M 323.

Trial Binder Content

Using the binder specific gravity, calculated volumes of effective and absorbed binder, and mass of aggregate per cm^3 of mix, the trial binder content can be determined for each trial blend.

$$P_{bi} = 100\left[\frac{G_b(V_{be} + V_{ba})}{(G_b(V_{be} + V_{ba})) + W_s}\right] \qquad 21$$

where:

P_{bi} = Initial trial binder content (percent by weight of total mix)
G_b = Specific gravity of the binder
V_{be} = Estimated volume of effective binder
V_{ba} = Estimated volume of absorbed binder
W_s = Mass of aggregate (grams) in 1 cm^3 of mix

Mix design software can be used to determine the initial trial binder content for each trial aggregate blend. If necessary refer to Appendix A1 of AASHTO R 35

Calculation Examples – (Using data from **Aggregate Blending Worksheet – Table 1)**

Mass of aggregate (grams) in one cm^3 of mix

Formula:

$$W_s = \frac{P_s(1 - V_a)}{\frac{P_b}{G_b} + \frac{P_s}{G_{se\_est}}}$$

Calculation Example:

$$W_s = \frac{(0.95)(0.96)}{\frac{0.05}{1.022} + \frac{0.95}{2.666}} = 2.2503927$$

Volume of absorbed binder (cm^3) in one cm^3 of mix

Formula:

$$V_{ba} = W_s\left(\frac{1}{G_{sb}} - \frac{1}{G_{se\_est}}\right)$$

Calculation Example:

$$V_{ba} = 2.2503927\left(\frac{1}{2.623} - \frac{1}{2.666}\right) = 0.0138378$$

Volume of effective binder (cm^3) in one cm^3 of mix

Formula:

$$V_{be} = 0.176 - (0.0675 \times \text{Log}(S_n))$$

Calculation Example:

$$V_{be} = 0.176 - (0.0675 \times 1.0969) = 0.1019593$$

Estimated binder content for the trial mixture

Formula:

$$P_{bi} = 100\left[\frac{G_b\left(V_{be} + V_{ba}\right)}{\left(G_b\left(V_{be} + V_{ba}\right)\right) + W_s}\right]$$

Calculation Example:

$$P_{bi} = 100\left[\frac{1.022\ \left(0.1019593 + 0.0138378\right)}{\left(1.022\ \left(0.1019593 + 0.0138378\right)\right)\ +\ 2.2503927}\right] = 4.996, \text{say } 5.00$$

22 Compacting Trial Blend Specimens

1. Prepare at least two replicate specimens at the initial trial binder content for each of the trial blends

23 ***Note:*** 4500 to 4700 grams of aggregate will usually be sufficient to compact specimens of 110 to 120mm height. Trial specimens may be necessary.

2. Prepare replicate specimens for theoretical maximum specific gravity (G_{mm}) (FOP for AASHTO T 209)
3. Mix and short term age the loose mix (FOP for AASHTO R 30)

24 **Mixing temperature: the middle of the range of temperature which the binder's kinematic viscosity is 0.17 ± 0.02 Pa-s.**

4. Obtain N_{ini}, N_{des} and N_{max} from Table 2 or the specifying agency

Note: *It may be advisable to compact an additional specimen to the N_{max} number of gyrations for each trial blend to assess conformance with the requirement at that number of gyrations. This will avoid continuing with a mixture that does not comply with all specified requirements.*

5. Compact specimens to N_{des} (FOP for AASHTO T 312)
6. Determine the bulk specific gravity (G_{mb}) of each specimen (FOP for AASHTO T 166 or T 275)
7. Obtain the theoretical maximum specific gravity (G_{mm}) for each combination from the companion samples

25 The Superpave volumetric mix design method uses gyratory compaction to fabricate the HMA specimens. The level of compaction in the Superpave Gyratory Compactor (SGC) is based on the design traffic that represents the 20-year design ESALs. The higher the design number of ESALs, the greater the number of required gyrations (See Table 2).

Table 2 – Superpave Gyratory Compaction Effort 26, 27

Design ESALS[1] (million)	Compaction Parameters			Typical Roadway Application[2]
	N_{ini}	N_{des}	N_{max}	
<0.3	6	50	75	Applications include roadways with very light traffic volumes such as local roads, county roads, and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate, or interstate. Special purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to <3	7	75	115	Applications include many collector roads or access streets. Medium-trafficked city streets and the majority of county roadways may be applicable to this level.
3 to <30	8	100	160	Applications include many two-lane, multilane, divided, and partially or completely controlled access roadways. Among these applications are medium to highly trafficked city streets, many state routes, US highways, and some rural interstates.
≥30	9	125	205	Applications include the vast majority of the US Interstate system, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level,

(1) The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

(2) As defined by “A Policy on Geometric design of Highways and Streets, 1994, AASHTO.

Evaluating Compacted Trial Mixtures

Determine the volumetric requirements according to Table 3.

V_a Calculation

(Air void is defined as the volume of the total HMA mix occupied by air in percent. It is calculated using the bulk specific gravity (G_{mb}) and the maximum theoretical specific gravity (G_{mm}).)

28

$$V_a = 100 * \left[1 - \left(\frac{G_{mb}}{G_{mm}}\right)\right]$$

Calculate Air Void Content for each blend:

VMA Calculation

(VMA is defined as the percent of volume of total mix that is not occupied by aggregate. It is the percent of volume of total mix occupied by the effective binder and air.)

29

$$VMA = 100 - \left(\frac{G_{mb} P_s}{G_{sb}}\right)$$

Calculate Voids in Mineral Aggregate (VMA) for each blend:

Where:

- G_{mb} = Bulk specific gravity of the extruded specimen
- G_{mm} = Theoretical maximum specific gravity of the mix
- P_s = Percent of aggregate in the mix = 100 - P_{bi}
- G_{sb} = Bulk specific gravity (oven-dry) of the combined aggregate

Calculation Examples:

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$$V_a = 100 \times \left[1 - \left(\frac{2.348}{2.468}\right)\right] = 4.86\%$$

31

$$VMA = 100 - \left(\frac{(2.348)(95.00)}{2.623}\right) = 14.96\%$$

where:

- G_{mm} = 2.468 Measured Theoretical Maximum Specific Gravity at Trial Binder Content
- G_{mb} = 2.348 Measured Average Bulk Specific Gravity of the Compacted Specimens
- P_s = 95.00 Percentage of Aggregate in the Trial Mixture
- G_{sb} = 2.623 Bulk Specific Gravity, oven-dry, of the Aggregate Blend

Evaluating Volumetric Properties 32

Although initial binder content was estimated for an air void content of 4.0% it is unlikely the actual air void content is exactly 4.0%. If the air void content does not fall within agency specification, a change in binder content is needed to obtain 4.0% air void content. The VMA change caused by the binder content change is estimated. These calculations permit the evaluation of VMA and VFA of each trial blend gradation at the same design air void content, 4.0 percent. Mix design software is generally used for these adjustments.

Estimating the Volumetric Properties at 4.0 percent Air Voids

1. Determine the difference in average air void content at N_{des} and 4.0% (ΔV_a).

Difference in Air Voids

$$\Delta V_a = 4.0 - V_a$$

V_a = Air void content of the trial aggregate gradation at N_{des}.
ΔV_a = Change in air void content

2. Estimate the change in binder content (ΔP_b) needed to change the air void content to 4.0%.

Change in Binder

$$\Delta P_b = -0.4(\Delta V_a)$$

ΔP_b = Change in binder percent

3. Calculate the new estimated binder content (P_{b_est}) required to achieve 4.0% air voids.

New Estimated Binder Content

$$P_{b\_est} = P_{bi} + \Delta P_b$$

P_{b_est} = Binder content estimated for 4.0% air voids
P_{bi} = Trial binder content actually used for blend
ΔP_b = Change in binder percent

4. Estimate the change in VMA (ΔVMA) caused by the change in air void content (ΔV_a) using the appropriate calculation below.

Change in VMA

$$\Delta VMA = 0.2(\Delta V_a) \quad \textbf{For } V_a > 4.0\%$$

or,

$$\Delta VMA = -0.1(\Delta V_a) \quad \textbf{For } V_a < 4.0\%$$

5. Calculate the VMA at N_{des} and 4.0% air voids.

VMA at N_{des}

$$VMA_{design} = VMA_{trial} + \Delta VMA$$

where:

VMA_{design} = VMA estimated at 4.0% air voids
VMA_{trial} = VMA at initial trial binder content

6. Using the value of ΔV_a estimate the relative density at N_{ini} when the air void content is adjusted to 4.0% at N_{des}.

Relative Density

$$\%G_{mm\_initial} = 100 * \left(\frac{G_{mb} h_d}{G_{mm} h_i} \right) - \Delta V_a$$

where:

$\%G_{mm\_initial}$ = Relative density at N_{ini} at the adjusted binder content.
h_d = Height of specimen after N_{des} gyrations
h_i = Height of specimen after N_{ini} gyrations

7. Calculate the actual Effective Specific Gravity (G_{se}) using measured G_{mm}.

Actual Effective Specific Gravity

$$G_{se} = \frac{P_{mm} - P_b}{\frac{P_{mm}}{G_{mm}} - \frac{P_b}{G_b}}$$

where:
G_{se} = Actual effective specific gravity
G_{mm} = Maximum specific gravity of mixture
P_{mm} = Percent by mass of total loose mix = 100
P_b = Binder content at which G_{mm} was performed
G_b = Specific gravity of binder

8. Estimate the percent of effective binder (P_{be_est}) and calculate the dust-to-binder ratio.

% Effective Binder

$$P_{be\_est} = -(P_s * G_b)\frac{(G_{se} - G_{sb})}{(G_{se} * G_{sb})} + P_{b\_est}$$

where:

P_{be_est} = Estimated effective binder content
P_s = Aggregate content, adjusted to 4.0% air voids = 100 - P_{b_est}
G_b = Specific gravity of binder
G_{se} = Actual effective specific gravity of aggregate
G_{sb} = Bulk specific gravity, oven-dry, of the combined aggregate
P_{b_est} = Estimated binder content to achieve 4.0% air voids

9. Estimate the dust to effective binder ratio.

Dust to Binder Ratio:

$$\text{dust} - \text{to} - \text{binder} = \frac{P_{0.075}}{P_{be\_est}}$$

where:

$P_{0.075}$ = Percent passing the #200 sieve.

Calculation Examples (Estimating Volumetric Properties at 4.0% Air Voids)

Given:

P_{bi}	= 5.00%	(from previous example, page 3-12)
V_a	= 4.86%	(from previous example, page 3-15)
VMA	= 14.96%	(from previous example, page 3-15)
$P_{0.075}$	= 4.8%	(minus No. 200 material from aggregate blend, page 3-5)
h_d	= 115.7 mm	(average height at N_{des} number of gyrations)
h_i	= 127.1 mm	(average height at N_{ini} number of gyrations)
G_{mb}	= 2.348	(measured average G_{mb} of extruded specimens)
G_{mm}	= 2.468	(measured G_{mm} of mix at P_{bi})
G_b	= 1.022	(binder specific gravity)

Difference in Air Voids

Difference in average air void content at N_{des} and 4.0% (ΔV_a).

Formula:

$$\Delta V_a = 4.0 - V_a$$

Calculation Example:

$$\Delta V_a = 4.0 - 4.86 = -0.86$$

V_a = air void content of the trial aggregate gradation at N_{des}
ΔV_a = change in air void content

Change in Binder Content

Estimated change in binder content (ΔP_b) needed to change the air void content to 4.0%.

Formula:

$$\Delta P_b = -0.4(\Delta V_a)$$

Calculation Example:

$$\Delta P_b = -0.4(-0.86) = 0.34$$

ΔP_b = change in binder percent

Estimated Binder Content to Achieve 4.0% Air Voids

Calculate the new estimated binder content (P_{b_est}) required to achieve 4.0% air voids.

Formula:

$$P_{b\_est} = P_{bi} + \Delta P_b$$

Calculation Example:

$$P_{b\_est} = 5.00 + 0.34 = 5.34$$

P_{b_est} = binder content estimated for 4.0% air voids

Change in VMA

Calculate the change in VMA at 4.0% air voids. Since V_a was greater than 4.0, use the appropriate formula.

Formula:

$$\Delta VMA = 0.2(\Delta V_a)$$

Calculation Example:

$$\Delta VMA = 0.2(-0.86) = -0.17$$

ΔVMA = change in VMA

VMA at N_{des}

Calculate the VMA adjusted to 4.0 air voids in the mixture.

Formula:

$$VMA_{design} = VMA_{trial} + \Delta VMA$$

Calculation Example:

$$VMA_{design} = 14.96 + (-0.17) = 14.79$$

VMA_{design} = VMA estimated at 4.0% air void
VMA_{trial} = VMA at initial trial binder content

Relative Density at N_{ini}

Using the value of ΔV_a estimate relative density at N_{ini} when the air void content is adjusted to 4.0% at N_{des}.

Formula:

$$\%G_{mm\_initial} = 100 * \left(\frac{G_{mb} h_d}{G_{mm} h_i} \right) - \Delta V_a$$

Calculation Example:

$$\%G_{mm\_initial} = 100 * \left(\frac{2.348 \times 115.7}{2.468 \times 127.1} \right) - (-0.86) = 87.5$$

$\%G_{mm\_initial}$ = Relative density at N_{ini} at the adjusted binder content.
h_d = 115.7 mm (Height of specimen after N_{des} gyrations)
h_i = 127.1 mm (Height of specimen after N_{ini} gyrations)
ΔV_a = –0.86 (Change in air void content)

Actual Effective Specific Gravity

Calculate the actual Effective Specific Gravity (G_{se}) using measured G_{mm}.

Formula:

$$G_{se} = \frac{P_{mm} - P_b}{\dfrac{P_{mm}}{G_{mm}} - \dfrac{P_b}{G_b}}$$

Calculation Example:

$$G_{se} = \frac{100 - 5.00}{\dfrac{100}{2.468} - \dfrac{5.00}{1.022}} = 2.6666, \text{say } 2.667$$

where:
G_{se} = Actual effective specific gravity
G_{mm} = 2.468 (Measured Theoretical Maximum Specific Gravity)
P_{mm} = 100 (Percent by mass of total loose mix)
P_b = 5.00 (Binder Content at which G_{mm} was performed)
G_b = 1.022 (Binder Specific Gravity)

% Effective Binder

Estimate the percent of effective binder (P_{be_est}).

Formula:

$$P_{be\_est} = -(P_s * G_b)\frac{(G_{se} - G_{sb})}{(G_{se} * G_{sb})} + P_{b\_est}$$

Calculation Example:

$$P_{be\_est} = -(94.66 * 1.022)\frac{(2.667 - 2.623)}{(2.667 * 2.623)} + 5.34 = 4.73$$

P_{be_est} = Estimated effective binder content
P_s = Aggregate content, adjusted to 4.0% air voids = 100 - P_{b_est}
G_b = Specific gravity of binder
G_{se} = Actual effective specific gravity of aggregate
G_{sb} = Bulk specific gravity, oven-dry, of the combined aggregate
P_{b_est} = Estimated binder content to achieve 4.0% air voids

Dust to Binder Ratio:

Estimate the dust to effective binder ratio.

Formula:

$$\text{dust} - \text{to} - \text{binder} = \frac{P_{0.075}}{P_{be\_est}}$$

Calculation Example:

$$\text{dust} - \text{to} - \text{binder} = \frac{4.8}{4.73} = 1.01$$

$P_{0.075}$ = Percent passing the #200 sieve.

Select the Best Design Aggregate Structure 33

Select the aggregate grading that best complies with all required Superpave properties for the next phase of the mix design process: the Optimum Binder Selection.

Selection of Design Aggregate Structure (Example) 34

Volumetric Property	Trial Mixture (1/2" Nominal Maximum Aggregate) 20-year Project Design ESALs = 5 million			Criteria
	1	**2**	3	
	At initial trial binder content			
P_b(trial)	5.2	**5.0**	4.8	
$\%G_{mm\ initial}$ (trial)	88.4	**86.6**	85.0	
$\%G_{mm\ des}$ (trial)	95.9	**95.14**	94.2	
V_a at N_{des}	4.1	**4.86**	5.8	4.0
VMA_{trial}	13.9	**14.96**	15.9	
	Adjustments to reach design binder content (V_a=4.0% at N_{des})			
ΔV_a	-0.1	**-0.86**	-1.8	
ΔP_b	0.0	**0.34**	0.7	
ΔVMA	0.0	**-0.17**	-0.4	
	At the estimated design content (V_a=4.0% at N_{des})			
Estimated P_b (design)	5.2	**5.34**	5.5	
VMA (design)	13.9	**14.79**	15.5	≥14.0
$\%G_{mm\ initial}$ (design)	88.5	**87.5**	86.8	<89.0

Notes: The top portion of this table presents measured densities and volumetric properties for specimens prepared for each trial aggregate blend at the initial trial binder content.

None of the specimens had an air void content of exactly 4.0 percent. Therefore, the procedures for adjustments was applied to: 1) estimate the design binder content at which V_a=4.0%, and 2) obtain adjusted relative density values at this estimated binder content.

The middle portion of this table presents the change in binder content (ΔP_b) and VMA (ΔVMA) that occurs when the air void content (V_a) is adjusted to 4.0 percent for each trial aggregate blend gradation.

The comparison of the VMA and densities at the estimated design binder content to the criteria in the last column shows that trial aggregate blend #1 does not have sufficient VMA (13.9% versus a requirement of ≥14.0). Trial blend #2 and Trial #3 meet the requirements for relative density and VMA and, in this example, either may be selected as the design aggregate gradation.

Trial Blend #2, shown in **bold**, was used for examples presented in the text.

2 Selecting Optimum Binder Content

The steps for selecting the optimum binder content are:

- Identify Mixtures
- Fabricate Specimens
- Compact Specimens to N_{des}
- Evaluate Volumetric properties at N_{des} for compliance with Superpave Criteria
- Select Optimum Binder Content
- Compact Replicate Specimens to N_{max}
- Evaluate Volumetric Properties at N_{max} for compliance with Superpave Criteria

3 Identify mixtures

Prepare a minimum of two replicate samples at each of the following four binder contents:

Estimated design binder content $P_{b\ est}$

0.5 percent below $P_{b\ est}$

0.5 percent above $P_{b\ est}$

1.0 percent above $P_{b\ est}$

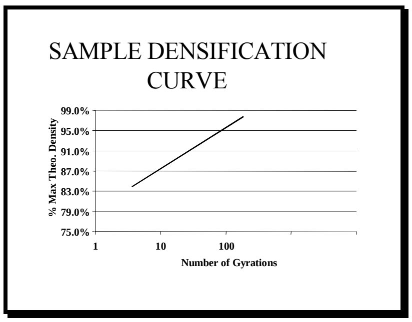
4 Fabricate and Compact Specimens

- Mix Specimens
- Age specimens (FOP for AASHTO R 30)
- Select compactive effort (gyrations)
- Compact replicate specimens according to the FOP for AASHTO T 312
  1. A minimum of 2 specimens at each of the 4 binder contents.
  2. Compact the replicate specimens to N_{des}

5 **Evaluate Volumetric Properties at N_{des}**

- Obtain height vs. number of gyrations for each specimen
- Determine the bulk specific gravity (G_{mb}) of each specimen according to the FOP for AASHTO T 166 or T 275 as appropriate.
- Obtain the theoretical maximum specific gravity (G_{mm}) according to the FOP for AASHTO T 209 for each combination from separate samples that have been mixed and conditioned in the same manner as the compacted specimens.

6 - For each of the four mixtures prepare a densification curve, representing % G_{mm} versus number of gyrations.



7

8 **Volumetric Properties**

Using the data from the replicate specimens, calculate the following for each of the four mixtures:

- V_a
- VMA
- VFA
- $P_{.075}/P_{be}$
- Density

Note: The volumetric properties are determined for each specimen and then averaged for each replicate mixture.

Calculate the Voids Filled with Asphalt (Binder)

$$VFA = 100 * \left(\frac{VMA - V_a}{VMA} \right)$$ 9

Calculate the dust to binder ratio

$$\text{Dust} - \text{to} - \text{binder} = \frac{P_{0.075}}{P_{be}}$$ 10

where:

P_{be} = Effective binder content

Determine the average corrected specimen relative densities at N_{ini} (% $G_{mm\ initial}$) for each of the four mixtures.

$$\%G_{mm\,initial} = 100 * \left(\frac{G_{mb} h_d}{G_{mm} h_i} \right)$$ 11

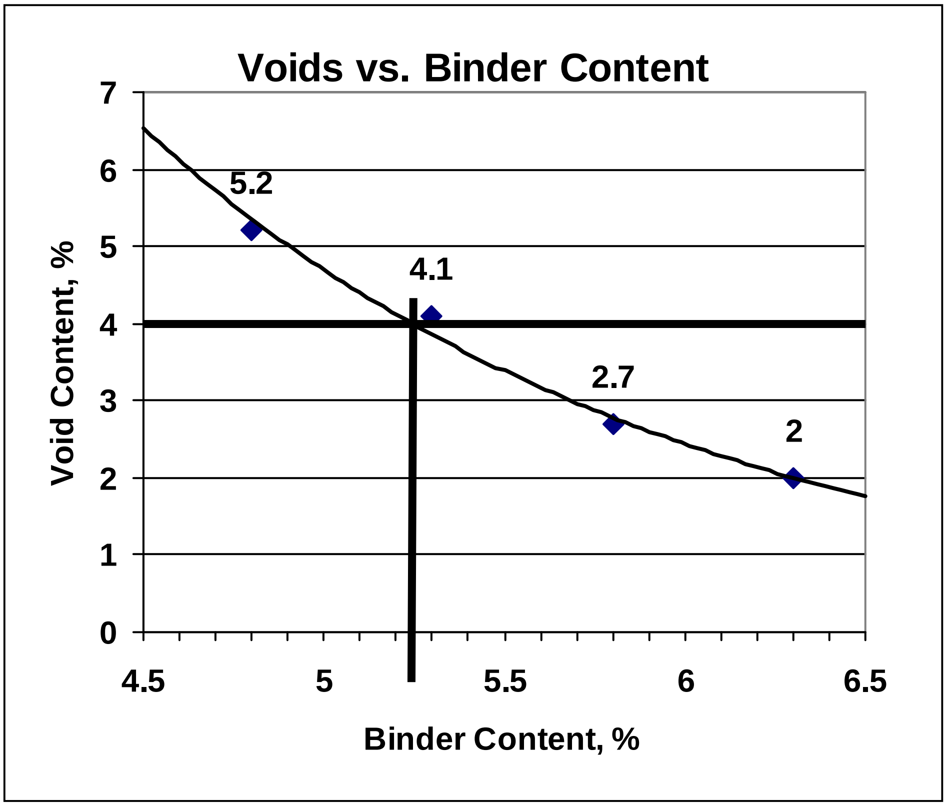
where:

$\%G_{mm\ initial}$ = Relative density at N_{ini}
h_d = Height of specimen after N_{des} gyrations
h_i = Height of specimen after N_{ini} gyrations

12 **Data Presentation**

- Plot the average V_a, VMA , VFA and relative density at N_{des} for replicate specimens versus binder content. Superpave software, or any spreadsheet software, can be used to generate the plots.

Air Voids (V_a) 13



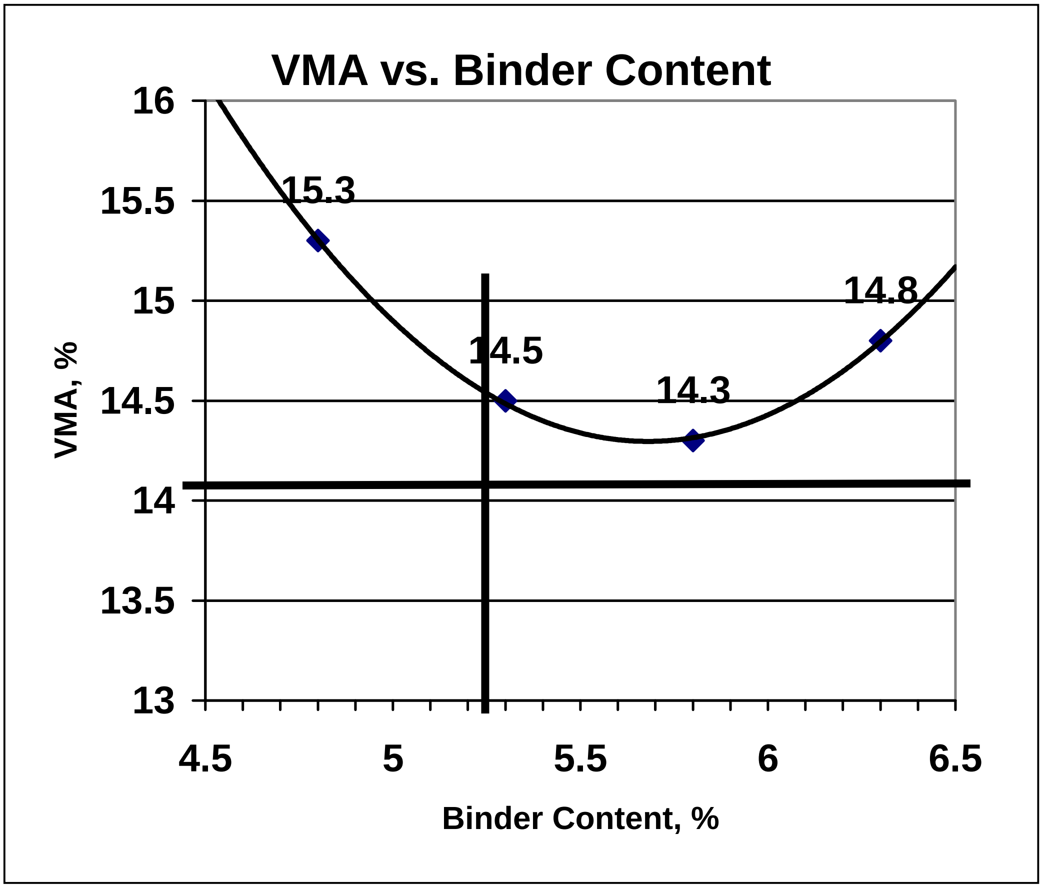
Air voids typically decrease as the percent binder content increases. On the graph the 4% V_a target is the horizontal line across the chart. The optimum binder content is the content at the point where the 4% criterion line intersects the air voids versus the binder content curve

14

Select Optimum Design Binder Content

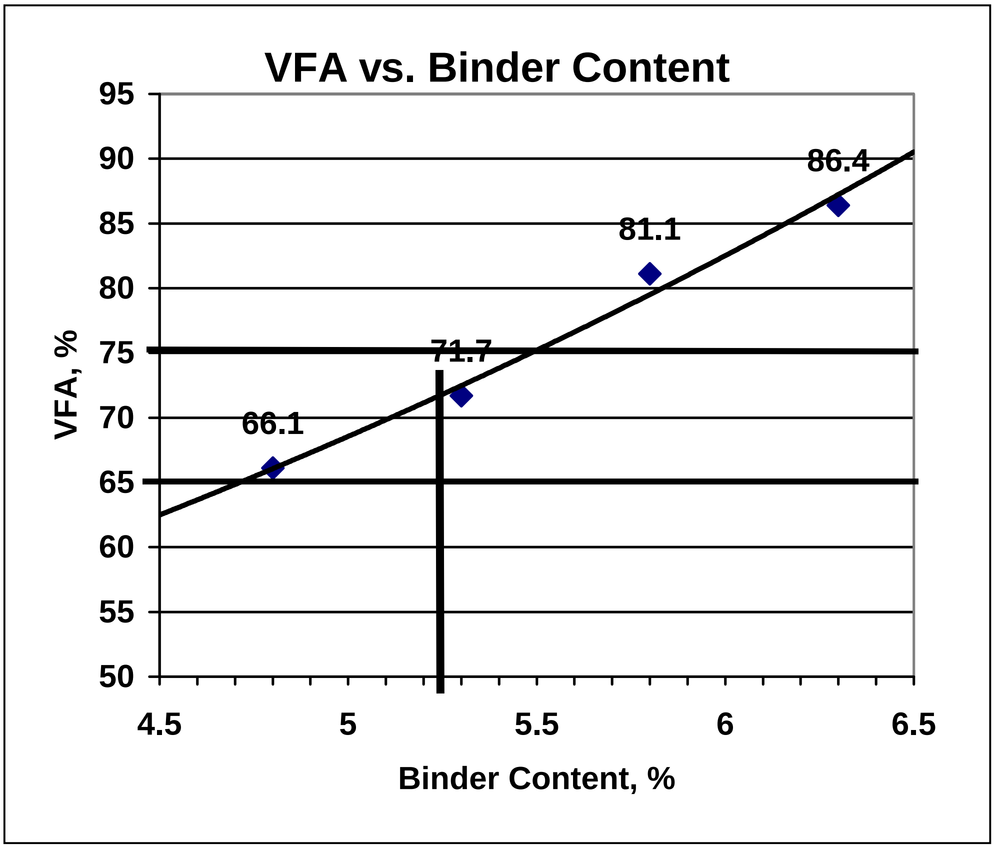
- Determine the binder content to the nearest 0.1 percent that corresponds with the target V_a of 4.0 percent, by graphical or mathematical interpolation.
- This is the design binder content (P_b) at N_{des}.

Voids in Mineral Aggregate (VMA) 15



The VMA decreases to a minimum value as binder content increases until the addition of more binder begins to push the aggregate apart, at this point the VMA increases. On this graph the VMA target is shown as a horizontal line (14%) across the chart. In this example all mixtures meet the Superpave VMA criterion.

Voids Filled With Asphalt (Binder) (VFA) 16

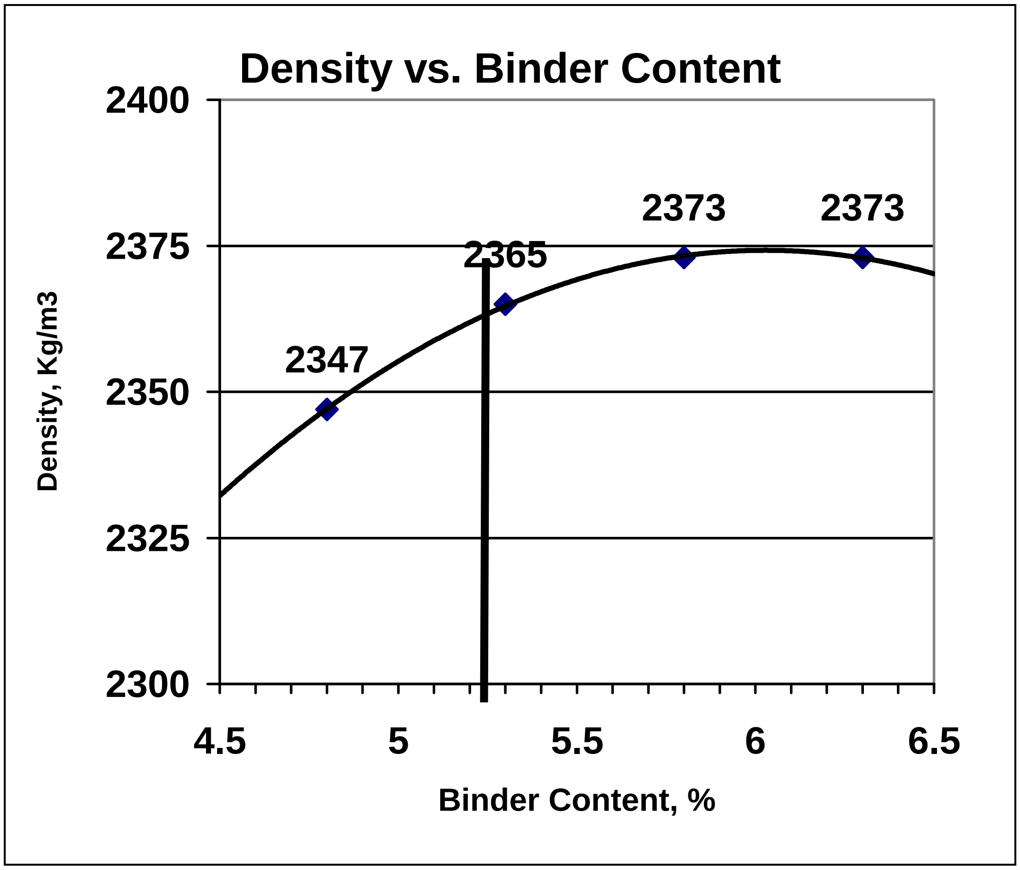


The VFA increases as the binder content increases. On this graph the VFA criterion is shown in terms of a minimum and maximum line across the chart. The % VFA at the selected design binder content should fall within the VFA criterion lines.

17 **Check Properties at Optimum**

- By interpolation obtain VMA, VFA and $P_{.075}/P_{be}$ at the selected optimum binder content.
- Check the VMA, VFA and $P_{.075}/P_b$ against the Superpave design criteria in Table 2.

Density at N_{des} 18



The density increases as the percent binder content increases up to a maximum and then it begins to decrease. This indicates that the binder is replacing the aggregate particles in the matrix.

19 **Determine % $G_{mm\ initial}$ at P_b**

1. Examine a plot of air void content versus binder content.
2. Determine the difference in air voids between 4.0 percent and the air void content at the nearest, lower binder content.
3. Determine the air void content at the nearest, lower binder content at its data point, not the line of best fit.
4. 20 Designate the difference in air void content as ΔV_a.
5. Determine the average corrected specimen relative density at N_{ini} at the nearest, lower binder content (below 4.0% air voids).
6. Calculate $\%G_{mm(initial)design}$. Confirm that the calculated value satisfies the design requirements in table 3 at the design binder content.

$$\%G_{mm\,initial} = 100*\left(\frac{G_{mb}h_d}{G_{mm}h_i}\right)$$ 21

where:

$\%G_{mm\ initial}$ = Relative density at N_{ini}
h_d = Height of specimen after N_{des} gyrations
h_i = Height of specimen after N_{ini} gyrations

$$\%G_{mm(initial)design} = \%G_{mm(initial)} - \Delta V_a$$ 22

where:

$\%G_{mm\ initial}$ =% G_{mm} at N_{ini} at the nearest lower binder content.

Calculation Examples – (See Voids vs. Binder Content Data, page 3-28)

Calculate $\%G_{mm\ initial}$ at the nearest lower binder content (4.8% binder content).

where:

G_{mm} at 4.8% Binder Content	= 2.476
G_{mb} at 4.8% Binder Content	= 2.347
h_d at 4.8% Binder Content	= 115.7 mm
h_i at 4.8% Binder Content	= 127.5 mm

Formula:

$$\%G_{mm\,initial} = 100*\left(\frac{G_{mb}h_d}{G_{mm}h_i}\right)$$

Calculation Example

$$\%G_{mm\,initial} = 100*\left(\frac{2.347 \times 115.7}{2.476 \times 127.5}\right) = 86.0$$

Calculate $\%G_{mm(initial)design}$

where:

V_a at nearest lower binder content	= 5.2%
ΔV_a	= −1.2% (4.0 – 5.2)

Formula:

$$\%G_{mm(initial)design} = \%G_{mm(initial)} - \Delta V_a$$

Calculation Example:

$$\%G_{mm(initial)design} = 86.0 - (-1.2) = 87.2$$ 23

24 **Measure $\%G_{mm}$ at N_{max}**

1. Prepare replicate specimens:
   a. Using the selected aggregate structure
   b. Using the selected optimum binder content
2. Condition the mixtures according to the FOP for AASHTO R 30

3. Compact the specimens to N_{max} in accordance with the FOP for AASHTO T 312

25 4. Measure the bulk specific gravity (G_{mb}) of the replicate specimens

5. Determine the average corrected specimen relative densities at N_{max} ($\%G_{mm\ max}$).

6. Confirm that $\% G_{mm\ max}$ satisfies the design requirements in Table 3 at the design binder content.

$$\%G_{mm\,max} = 100\frac{G_{mb}}{G_{mm}}$$

where:

$\%G_{mm\ max}$ = relative density at N_{max} gyrations at the design binder content

26 **Evaluate Moisture Susceptibility**

Evaluate moisture susceptibility by testing replicate specimens in accordance with the FOP for AASHTO T 283.

Note: If the tensile strength ratio is less than 0.80 then remedial action is required. If remedial agents are used such as anti-strip agents or mineral admixtures, retest the mix to assure compliance with the 0.80 minimum requirement and verify the volumetric properties.

27 **Check Superpave Criteria**

- Check all properties at the selected optimum binder content against the Superpave criteria.
  - –V_a
  - –VMA
  - –VFA
  - –$P_{.075}/P_{be}$
  - –$\% G_{mm\ initial}$
  - –$\% G_{mm\ max}$
- Final design should meet all Superpave criteria in Table 3.

Table 3 – Superpave HMA Design Requirements

28

Design Esals[1] (million)	**Required Relative Density (% of Theoretical Maximum Specific Gravity)**			**Voids in Mineral Aggregate**[7] **Percent Minimum**						% Voids Filled with Asphalt (VFA) Range[2]	Dust-to-Binder Ratio Range[3]
				Nominal Maximum Aggregate Size							
	N_{ini}	**N_{des}**	**N_{max}**	1½”	1”	3/4"	1/2"	3/8”	#4		
<0.3	≤91.5									70-80[4]	
0.3 to <3	≤90.5									65-78	
3 to <10		96.0[6]	≤98.0	11.0	12.0	13.0	14.0	15.0	16.0		0.6-1.2
10 to <30	≤89.0									65-75[5]	
≥30											

(1) The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.
(2) For 1½-inch nominal maximum size mixtures, the specified lower limit of the VFA range is 64% for all traffic levels.
(3) For #4 nominal maximum size mixtures, the dust-to-binder ratio shall be 0.9 to 2.0.
(4) For 1 inch nominal maximum size mixtures, the specified lower limit of the VFA shall be 67 percent for design traffic levels < 0.3 million ESALs.
(5) For design traffic levels >3 million ESALs, 3/8 inch nominal maximum size mixtures, the specified VFA range shall be 73 to 76 percent and for #4 nominal maximum size mixtures shall be 75 to 78 percent.
(6) Corresponds to an Air Void Content (V_a) of 4.0%.
(7) VMA greater than 2% above the minimum should be avoided.

Adjusting the Mixture to Meet Properties

29 **Adjusting VMA.** To change the design aggregate skeleton to meet specified VMA, there are three likely options:

1. Change the gradation, only if the trial aggregate blend gradation analysis did not include the full spectrum of the gradation control area.
2. Reduce or increase the minus #200 fraction, (reduction will increase VMA, increase will lower VMA). This is only viable if the minus #200 is not already at the lower or upper limits.
3. Change the texture and /or shape of the aggregate fractions; this would require further processing of existing material or a change in aggregate sources.

30 **Adjusting VFA.** The lower limit of the VFA range should always be met at 4.0 percent air voids if the VMA meet the requirements. If the VFA is too high then the VMA will be too high. If so, redesign the mixture to reduce VMA.

Options include:

1. Change gradation so that it is closer to the maximum density line.
2. Increase the minus #200 fraction if there is room within the specification control points.
3. Change the surface texture and shape of the aggregates.

31 **Adjusting the Tensile Strength Ratio.** The tensile strength ratio can be increased by:

1. Adding chemical anti-strip agents to the binder to promote adhesion in the presence of water.
2. Adding mineral admixtures.

32 Report

Project number
Traffic level
Mix design number
Design aggregate structure
- Source of aggregate
- Kind of aggregate
- Source and amount of RAP
- RAP quality characteristics and gradation

33 Design binder source and grade
HMA design characteristics:
- Percent binder
- Relative density
- N values
- VMA
- VFA
- V_a
- V_{be} and V_{ba}
- Dust-to-binder ratio

Tips! 34

- Check that the binder grade matches project climate conditions
- Be sure that aggregates obtained for the design accurately represent stockpiled materials
- Select compactive effort based on 20 year design ESAL's
- Select 3 trial blends encompassing the range of allowable gradations
- Condition G_{mm} samples the same as for compacted specimens 35
- Be sure that **all** volumetric properties are met before finalizing gradation selection
- Check and re-check all properties at P_b before reporting data

REVIEW QUESTIONS

1. Describe the aggregate preparation steps prior to combining to a target grading.

2. How is the combined aggregate grading determined for a trial gradation?

3. How many trial aggregate gradations must be prepared?

4. What constitutes an acceptable trial aggregate gradation?

5. For design ESAL's of 4 million, what is the number of gyrations used to compact the specimens during the aggregate selection phase, when the nominal maximum size is ¾ inch and the VMA required is 13.0%?

6. Calculate the VMA when traffic level is 2.8 million ESAL's, G_{mm} is 2.517, G_{mb} is 2.398, V_a is 4.7%, P_s is 95.2%, and G_{sb} is 2.639. Would this meet the requirements for a ½ inch nominal maximum size mix?

7. Given the above noted data, calculate V_a. How could this data be used in selection of binder content for a mix design?

8. Given the data from No. 6 above, calculate the VFA. Does this meet the requirements for a ¾ inch nominal maximum size?

9. Calculate the $\%G_{mm}$ at N_{max} for a compacted HMA specimen where the level of compaction was 205 gyrations, design ESAL's were 38 million, G_{mm} was 2.523, P_s was 95.9, G_{sb} was 2.714, and G_{mb} was 2.482. Does this comply with Superpave HMA Design Requirements?

Practice Practical – R 35 Trial Mixtures

Pavement parameters

Maximum seven-day average pavement design temperature: **50°C**.
Minimum pavement design temperature: **-20° C**.
20-year design ESAL's: **26 million**
Pavement Type: **Surface Course**
Traffic Speed : **Slow**

Given:

Binder Specific Gravity: **1.020**

Multiplier to be used for estimating effective aggregate specific gravity: **0.7**

Test Questions

1- Using the pavement parameters shown above, determine the required binder grade and number of gyrations for the project. Record in the appropriate spaces on page 3-40.

2- Individual aggregate gradations specific gravities, and absorptions are given on the aggregate table (page 3-39). Using them, develop at least one gradation that meets the specified requirements for a mix having a nominal maximum size of: **3/4-inch (19 mm)**. Record the data for your gradation in the space shown for "Combined Grading." Also calculate, and record in the space provided on the table, the combined specific gravities and absorption for your blend.

3- Using the specific gravities and the appropriate formulas from R 35, calculate and record estimated G_{se}, W_s, V_{ba}, V_{be}, and the trial binder content (P_{bi}). Space is provided on page 3-40 to record these values.

4- Using the trial mixture and compaction data for G_{mm}, height, and G_{mb} shown on page 3-40, calculate and/or record all values needed to evaluate the trial blend.

5- Calculate and record the volumetric properties adjusted to 4.0% voids.

6- Verify values meet the requirements of the FOP for AASHTO M 323.

Helpful information:

log 4.75	0.6767	log 19	1.2788
log 9.5	0.9777	log 25	1.3979
log 12.5	1.0969	log 37.5	1.5740

Available binders to choose from:

PG	52 -16	PG	58 -28	PG	64 -40
PG	52 -22	PG	58 -34	PG	70 -16
PG	52 -28	PG	58 -40	PG	70 -22
PG	52 -34	PG	64 -16	PG	70 -28
PG	52 -40	PG	64 -22	PG	70 -34
PG	58 -16	PG	64 -28	PG	70 -40
PG	58 -22	PG	64 -34		

Aggregate Blending Worksheet

Product Identification	Percentage of Products Used (Decimal)					
	Blend No. 1	**a** (3/4")	**b** (1/2")	**c** (3/8")	**d** (1/4")	**e** (Fine)
A (3/4")						
B (1/2")						
C (3/8")						
D (1/4")						
E (Fine)						
Total	1.00					

Grading for 3/4" (19 mm) Mix						
Sieve Size	Comb.	Individual Product Contributions				
1"						
3/4"						
1/2"						
3/8"						
No. 4						
No. 8						
No. 16						
No. 30						
No. 50						
No. 100						
No. 200						
Combined Specific Gravity and Absorption						
G_{sb} (OD)						
G_{sb} (SSD)						
G_{sa}						
Absorption						

	Individual Product Identification and Gradations				
Sieve Size	**A** (3/4")	**B** (1/2")	**C** (3/8")	**D** (1/4")	**E** (Fine)
1"	100	100	100	100	100
3/4"	100	100	100	100	100
1/2"	10	91	100	100	100
3/8"	5	12	96	100	100
No. 4	3	2	20	75	100
No. 8	1	2	15	21	95
No. 16	1	2	5	10	78
No. 30	1	1	2	5	46
No. 50	1	1	2	3	25
No. 100	1	1	2	3	18
No. 200	0.2	0.3	1.5	2.0	10.3
Specific Gravity and Absorption					
G_{sb} (OD)	2.630	2.643	2.641	2.589	2.610
G_{sb} (SSD)	2.647	2.655	2.654	2.626	2.635
G_{sa}	2.676	2.673	2.676	2.689	2.677
Absorption	0.53	0.40	0.45	0.98	0.90

Trial Blend Properties

PG Binder Grade ____________________

Mix Gyrations: N_{ini} __________ N_{des} __________ N_{max} __________

$G_{se\ est}$ __________ W_s __________

G_b __________ V_{ba} __________

P_{bi} __________ V_{be} __________

TRIAL MIXTURE AND COMPACTION DATA

G_{mm} 2.492

Gyratory Height Data

Specimen	1	2
@N_{ini}	125.9	128.3
@N_{des}	114.3	117.1

Bulk Specific Gravity Data (G_{mb})

Specimen	1	2	Average
	2.367	2.359	__________

VOLUMETRIC SUMMARY OF TRIAL MIXTURE
(Calculate using appropriate values and formulas)

V_a _______ G_{se} _______ (actual G_{se}, not estimated value)

VMA _______ VFA _______

VOLUMETRIC SUMMARY OF TRIAL MIXTURE CORRECTED TO V_a OF 4.0%

$P_{b\ est\ design}$ _______ Δ V_a _______

VMA_{design} _______ Δ P_b _______

VFA_{design} _______ Δ VMA _______

$\%G_{mm\ initial}$ _______ P_s _______

$P_{be\ est}$ _______ Minus # 200 _______

Dust to Binder Ratio _______